Numerical Simulations of Energetic Internal Waves in Irregular Bathymetries

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LONG-TERM GOAL

My long term goals are to develop validated numerical models suitable for detailed, process oriented studies, to apply these models to a broad class of oceanographically relevant flows and to use the results of these studies to develop simple conceptual models with predictive capability.

OBJECTIVES

The objective of this study is to better understand the effects of mixing and dissipation in hydraulically controlled flows, in particular, the implications of these processes for volume and tracer transport. A specific objective is to understand the processes determining the features observed in the vicinity of the central contraction in the Bosphorus Strait. A further objective is to extend the range of problems amenable to the numerical model developed in this project by incorporating variable bottom topography, e.g. for continuously-stratified flow over two-dimensional sills.

APPROACH

This study is a collaborative effort with Dr. Harvey Seim at the Skidaway Institute of Oceanography. Our approach is to develop and apply a three-dimensional LES model for continuously-stratified exchange flow through a contracting channel. A series of "lock-exchange" problems were formulated and run with sufficient resolution to capture the formation of interfacial instabilities. The numerical results are being compared with predictions based on inviscid two-layer hydraulics and with observed flows in Gibraltar and the Bosphorus. A series of parallel laboratory/numerical experiments are being conducted to exercise and test the numerical model under a variety of flow conditions. These studies are collaborative with Dr. Greg Ivey and students at the Centre for Water Research, University of Western Australia.

WORK COMPLETED

Development of the numerical model has been completed and an extensive sequence of validation and internal consistency checks has been conducted. These checks include validation and convergence tests against analytical solutions, continuous monitoring of kinetic and potential energy balances and pointwise comparisons with laboratory data. The allowable geometry of the computational domain has been extended to permit simulation of flow over bottom topography that varies in one direction. A manuscript documenting the numerical techniques and the validation procedure has been submitted.

Report Documentation Page					Form Approved OMB No. 0704-0188
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE **1998**		2. REPORT TYPE			3. DATES COVERED **00-00-1998 to 00-00-1998**
4. TITLE AND SUBTITLE **Numerical Simulations of Energetic Internal Waves in Irregular Bathymetrics**					5a. CONTRACT NUMBER
					5b. GRANT NUMBER
					5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)					5d. PROJECT NUMBER
					5e. TASK NUMBER
					5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Washington,Applied Physics Laboratory,1013 NE 40th Street,Seattle,WA,98195**					8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)					10. SPONSOR/MONITOR’S ACRONYM(S)
					11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**					
13. SUPPLEMENTARY NOTES **See also ADM002252.**					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

The exchange flow simulations are performed in an open domain, i.e. fluid enters and exits at the up- and downstream boundaries. The open boundaries are assumed to be well within a long channel connecting two reservoirs but also well up- and downstream of a channel constriction. The external parameters for exchange flow in this configuration are the density difference between the reservoirs, the channel geometry and the barotropic pressure drop maintained across the contraction. To compare the computed solutions with two-layer hydraulic theory, the relationship between this problem and the classical exchange flow, i.e. where the flow rate ratio and reservoir conditions are specified, was determined.

A series of simulations were conducted where the channel geometry, consisting of a single mid-channel contraction, and the density difference between the reservoirs were held fixed. The runs were initialized as lock exchange problems, light and heavy fluid to either side of the channel throat which was allowed to flow for t>0. The nature of the flow, in particular the positions of the hydraulic controls, the transport of fluid and density and the properties of the interfacial layer of mixed fluid were quantified as the magnitude of the imposed barotropic pressure drop across the contraction was varied. The simulated flows correspond to the "moderately barotropic" regime of Armi and Farmer, 1986. A manuscript documenting this work has been submitted.

The results of the simulations, in particular those for submaximal exchange, are being interpreted in light of the ongoing analysis of the data taken from the Bosphorus by Mike Gregg (assisted by Seim and myself). See the report by Harvey Seim for a discussion of the Bosphorus data analysis.

A series of initial simulations of wave breaking at a sloping boundary have also been made. In these simulations, a solitary wave of depression travels along a thin pycnocline toward a sloping bed. The wave breaks at the boundary and mixed fluid is ejected from the boundary layer to the interior of the basin. At issue is the mixing and, in particular, the adjustment of the flow after the mixing occurs. The numerical simulation has been set up to match approximately (limitations due to grid orthogonality prevent an exact match) the laboratory configuration of Michallet and Ivey (1998). Dye visualizations, instantaneous velocity fields obtained from PIV techniques, displacement time series and estimates of mixing efficiency are available from the laboratory study for comparison. Initial comparisons of the velocity field, in particular the convergence of up- and down-slope boundary jets are encouraging.

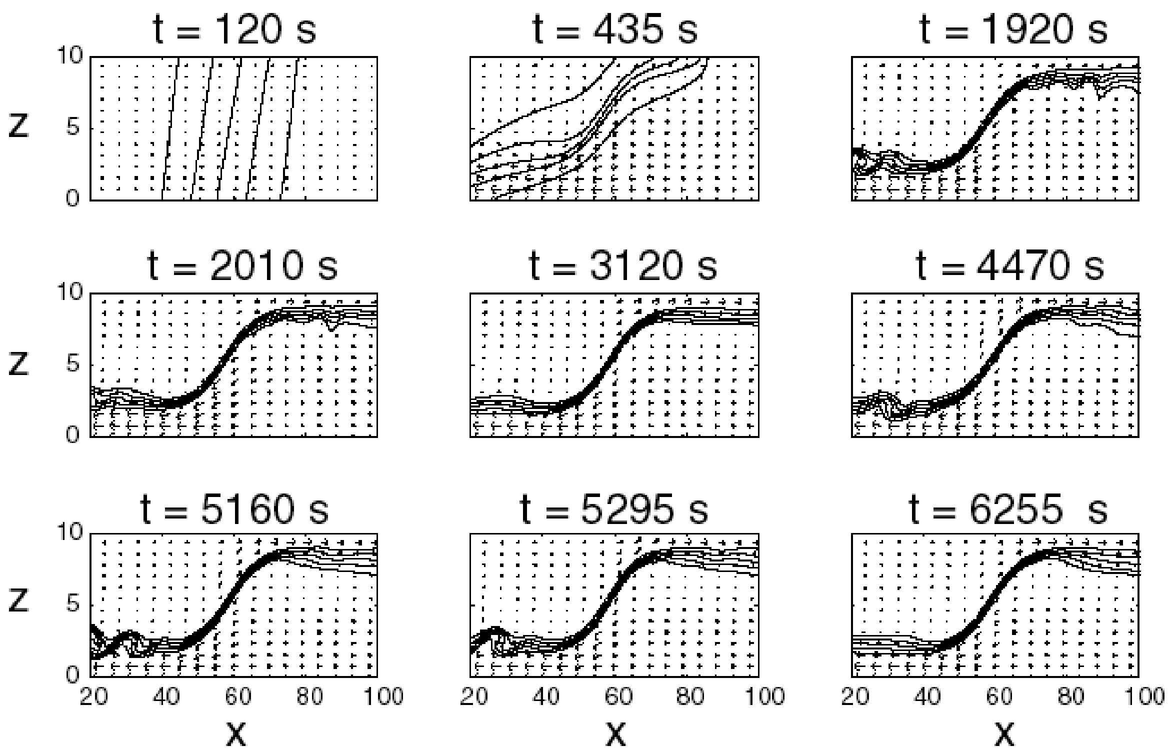
Preliminary runs of density currents down sills have been made in preparation for a study of tidally forced flow over sills. This study is in its early stages.

In collaboration with Greg Ivey and Prabath DeSilva, the analysis of a laboratory experiment of a steady, wave-energized turbulent boundary layer at a sloping bed has been completed and a manuscript submitted.

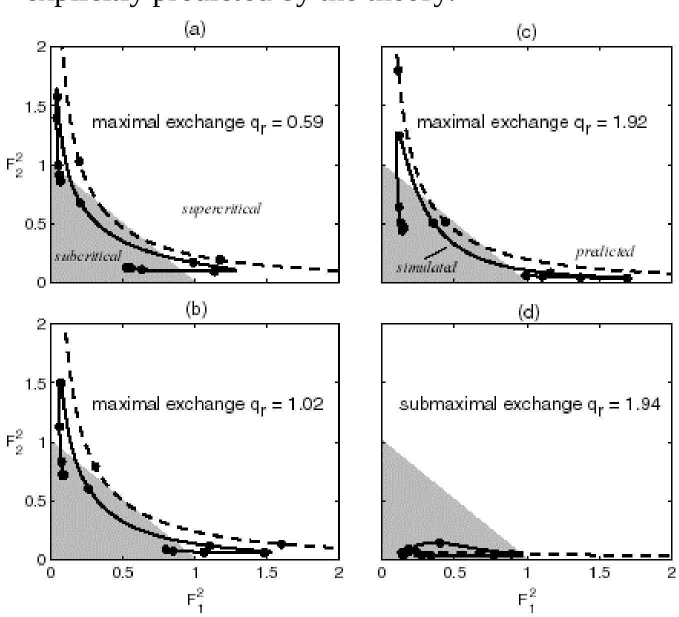
RESULTS

A series of lock exchange initial value problems were run in a symmetric contracting channel. In these flows, baroclinic pressure forces drive an underflow from right to left (see figure below). A barotropic pressure drop across the contraction opposes this flow and induces a surface counter-flow. By adjusting the magnitude of the imposed pressure drop, the total barotropic component of the exchange flows was controlled. The figure below shows a representative snapshot of the mid-channel vertical plane. The density of the inflowing fluid was held fixed, at $\rho_1 < \rho_2$ for fluid entering from the left and at

ρ_2 for fluid entering from the right. In these simulations, the presence of fluid with densities between these extreme values indicates diapycnal mixing.

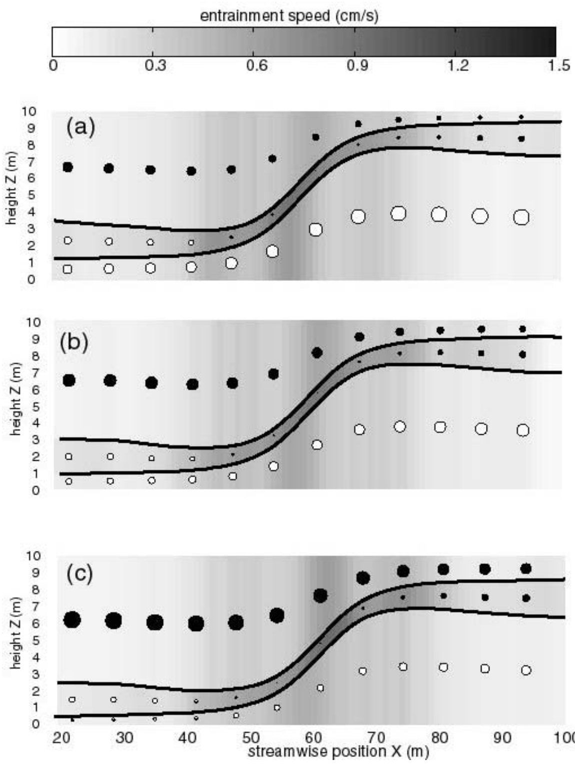


Using a two-layer decomposition of the computed solutions, with the layer definitions based on the flow direction, the layer and composite Froude numbers were computed. These values, along with the predicted values based on two-layer inviscid hydraulics, are shown below (c.f. Armi and Farmer, 1986). Generally, the simulated flows have lower Fr and the spatial extent of the subcritical region near the contraction is larger than predicted. The supercritical regions at the contraction exits are quite small in the computed flows owing to relaxation at hydraulic jumps, which are known to occur but not explicitly predicted by the theory.



Solid curves show computed Fr numbers, dashed curves those predicted by two-layer hydraulics. Values plotted are parameterized by channel position. Left to right through the contraction corresponds to upper left to lower right in the Fr plane. Shaded region indicates subcritical flow according to hydraulic theory. Panels (a)-(c) are taken from simulations of maximal exchange, panel (d) from a submaximal case. In (d), the simulated flow only barely achieves a supercritical state at only one point along the channel before returning to subcritical conditions as a result of intense billowing and mixing.

A closer inspection of the computed solutions reveals the inadequacy of a two-layer description of the flow. Following Bray et al 1995, we decomposed the flow into three-layers; two nearly homogeneous layers separated by a stratified interfacial layer. The properties of the interfacial layer, i.e. its position, thickness and the magnitude and direction of the interfacial layer transport were evaluated as a function of streamwise position for several quasi-steady exchange flows. The figure below shows the simulated layer properties as well as the magnitude of the flux between the layers. The three panels show the results for net barotropic flow to the left, approximately zero and to the right respectively.



The size of the circles are proportional to the transport carried by each layer, open and closed circles indicate transport to the left or right respectively. The shading indicates the rate of entrainment, expressed as a speed, of each layer. The bounding layers lose fluid to the interfacial layer. The overall characteristics of the interfacial layer are similar to those observed for the mean flow in Gibraltar by Bray et al 1995: the layer is thinnest near the hydraulic controls, increasing in thickness with distance away. The interfacial transport is to either direction away from the control and carries a significant fraction of the total horizontal transport. Mixing results in a reduced lateral tracer flux compared to inviscid hydraulic predictions, consistent with laboratory measurements. The layer transports and fluxes were computed using time and cross-channel averaged flow fields in quasi-steady state (time variability due primarily to billowing

Maximal exchange flows have two hydraulic controls and thus both the upper and lower layers thin and become supercritical to either side of the contraction. In the first set of simulations, we focused on the interior dynamics, ignoring the effects of bottom friction by imposing free-slip boundary conditions. To gauge the effect of bottom stress, we then repeated some runs with a no flow bottom boundary condition. This change had a dramatic effect on the nature of the solution: the stress on the lower layer prevented it from becoming supercritical. The flow to the subcritical side of the contraction was characterized by a tight, stable density interface at mid-depth. On the other side (downstream with respect to the net barotropic flow), the upper layer thins, barely achieves supercriticality and is characterized by a chaotic shedding of billow-like structures and intense mixing.

A new scaling analysis of the Winters and D'Asaro 1996 formula for diapycnal diffusivity has yielded a relationship between diapycnal diffusivity and TKE dissipation rate based on first principles and without defining mixing in terms of a net advective flux. The analysis suggests that the diffusivity is proportional to ε/N^2 for weak turbulence with $\varepsilon/\nu N^2$ of order 1. For more energetic turbulence, the analysis predicts a scaling like $(\varepsilon/\nu N^2)^{3/2}$. The analysis overpredicts the diffusivity in highly energetic turbulence (the unstratified limit) but the range of validity is not yet known.

IMPLICATIONS/APPLICATIONS

The numerical simulations of exchange flow suggest that entrainment and mixing are important processes in hydraulically controlled flows. As observed by Bray et al (1995), the interfacial layer carries a significant fraction of the total transport. The characteristics of the interfacial layer appear to be determined by turbulent mixing in the controlled section of the flow. These results suggest that determination of volumetric transport from the lateral salt (or density) flux may result in a significant underestimate. The numerical results are consistent with the experiment of Helfrich (1995) in that mixing resulted in significantly reduced tracer transport relative to inviscid hydraulic prediction.

This work suggests the need for new conceptual models for hydraulically controlled flow. Models are needed that intrinsically incorporate an interfacial layer, the properties of which are determined by entrainment or flux from the bounding layers.

The scaling analysis of the Winters and D'Asaro formula for diapycnal flux yields a testable prediction of diapycnal diffusivity in a regime (weak stratified turbulence) where previous theories predict flux at molecular values. For salt stratified fluids, the difference can be as large as a few orders of magnitude. If validated (laboratory experiments are underway), this result could alter our inferences of mixing rates based on dissipation measurements in weakly turbulent flows.

TRANSITIONS

The numerical models developed for this project are currently being used by two Ph.D. students supervised jointly by Dr. Greg Ivey and myself at the Centre for Water Research, University of Western Australia. Tim Finnigan is investigating exchange flow over a sill driven by spatially localized surface buoyancy flux. Andy Hogg is investigating the role of instabilities and mixing in determining volumetric and tracer transport in exchange flows through contracting channels. Both studies are using a combined numerical/laboratory experimental approach.

A set of codes, developed under ONR funding, for calculating stable and unstable eigenfunctions for continuously stratified, sheared velocity profiles was recently employed by Dr. Larry Pratt at WHOI as part of his investigation of Red Sea dynamics.

The techniques for diagnosing diapycnal mixing proposed by Winters et al 1995 and Winters and D'Asaro 1996 have been employed in a study of numerical diffusion induced by different approximation techniques for advection in large-scale circulation models by Griffies, Pacanowski and Hallberg (1998).

A laboratory facility has been constructed and experiments are now underway to investigate the implications of the Winters and D'Asaro (1996) analysis of diapycnal flux and the scaling of this prediction (Ivey at al 1999) in terms of the dissipation rate of kinetic energy.

RELATED PROJECTS

The modeling of exchange flows is being undertaken as part of a collaborative study of the Bosphorus with Dr's. Mike Gregg and Harvey Seim.

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